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7.—THE OCCURRENCE OF ANDALUSITE, KYANITE, SILLIMANITE AND STAUROLITE IN THE CHITTERING VALLEY.

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The Chittering valley runs almost due south, with some minor bends, along the 116th meridian for 35 miles from a little south of Wannamal to its junction with the Swan valley east of Bullsbrook. The stream has been guided in its flow by a series of Precambrian schists and granitic gneisses which strike approximately north, and are apparently vertically bedded. Both classes of rock are intersected by greenstone dykes, which are mostly either massive epidiorites or hornblende schists.

The sedimentary schists are characterised throughout by an abundance of quartz and biotite, associated with variable amounts of muscovite and chlorite. The relative proportions of biotite and quartz vary from point to point, and bed to bed, the rocks ranging from micaceous sandstones to biotite schists. Small quartz veins and lenses are common in them, and still smaller veins and ill-defined masses of pegmatite are present, but are rather rare. Owing to deep seated alteration, kyanite, sillimanite and staurolite have been generated in a number of places, and andalusite and corundum in at least one. The original rocks have apparently been sandstones and shales, both probably glauconitic or tuffaceous, which would account for the unusual conjunction of quartz and biotite, and for part, at least, of the high content of the rocks in potash and iron.

Sillimanite seems to be confined to the more siliceous rocks. Kyanite and staurolite occur in all types, but the largest and most abundant staurolite is in the most highly biotitic rocks. Both minerals are often more plentiful in the immediate walls of quartz veins, and several occurrences are known of kyanite embedded in vein quartz. Staurolite is not found actually in vein quartz, and only one occurrence is known of its matrix being a pegmatite.

The areas in which the minerals have been studied are, in order from south to north.

Lower Chittering—Bullsbrook Road, Marbling Brook, Goyamin Pool.

Middle Chittering—Toodyay Road, Chittering Lake, South Bindoon.

Upper Chittering—Wattle Flat.

Further north, on the same strike, specimens of kyanite have been sent to the writer from Wannamal, and he has examined in person an extensive development of staurolite schist at Gillingarra. These places are respectively seven and 21 miles north of Wattle Flat, beyond the head of the Chittering Valley, but on what is undoubtedly an extension of the Chittering rocks.

Bullsbrook Road (Lower Chittering). This includes the country within a three-mile radius of C.G.* 200, where the road running east from Bullsbrook impinges on the Chittering Brook, four miles N. of its confluence with the Swan.

In the valley running east through C.G. 1260, J. E. Wells first found the only evidence of *andalusite* in the Chittering Valley in the form of large and small subangular pseudomorphs of muscovite after andalusite, plentifully embedded in a series of beds of mica schist interstratified with bands of granite, striking about 350 deg. The two rocks are in bands 10 to 50 yards (10 to 45 metres) wide, traversed at intervals by small epidiorite dykes. At first sight the "eyes" or "knots" in the schist resemble some of those of fresh andalusite in the Jimperding Valley 14 miles to the north-east, but their softness indicates their alteration, and this is confirmed by microscopic examination. A section of a typical pseudomorph shows it to be almost wholly composed of minutely scaly muscovite, slightly iron-stained, and enclosing a few brown granular masses of altered chlorite, and occasional large scales of muscovite. These pseudomorphs range from one to 10 cm. in length and reach 200 grams in weight. One band of schist in this series carries corundum, the individual crystals of which are also either wholly or partly altered to sericite.†

Near the east boundary of C.G. 826, and on the south side of Plunkett's Mill road, there is a siliceous mica schist, much contorted and weathered in which both sillimanite and kyanite occur in conjunction. *Sillimanite* is by far the more plentiful and forms a considerable proportion of the whole rock, mostly in dense fibrous bundles of milk white colour and satiny sheen, reaching a centimetre in diameter, and six centimetres in length. In addition, it is seen in thin lenses and fan-like groups of fibres. In some specimens sillimanite constitutes 30 to 40 per cent. of the whole rock. Some of the mineral from a large bundle was found to have a specific gravity between 3.15 and 3.25, and to show straight extinction, with elongation optically positive. The associated *kyanite* is in single isolated colourless crystals 2 to 3 mm. long and about 0.5 mm. in diameter. They are fairly common in the more micaceous layers and possess the characteristic angular forms with oblique extinction. A few yards east of the sillimanite rock is a band of quartz-mica schist thickly studded with small white or yellowish kyanite crystals.

From the summit of the range about a mile east of C.G. 818 come the most beautiful specimens of *kyanite* obtainable in the Chittering Valley. This occurrence has already been referred to by the writer in a previous contribution.‡ Here large transparent and translucent crystals occur in vein quartz, the colours ranging from "orient blue," through "Alice blue" to "sky grey" (R 45″ to 45″ f), rarely "sky blue" (47′ d) or "Yale blue" (47′ b). At the extreme northern end of the vein some of the kyanite is quite colourless and associated with other crystals just faintly tinged with blue. The vein has been traced for about 50 yards (45 metres) on a bearing 340 deg. following the contact of a greenstone dyke with a mica schist. At the south end it passes under primary laterite; at the north end it is cut off by a cross dyke of greenstone.

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* C.G. = Crown Grant. † See this volume, p. 66. ‡ J.R.S.W.A. 12, pp. 62, 63.

Marbling Brook. The hill on C.G. 570 immediately to the north of the junction of Marbling Brook and Chittering Brook is composed of beds of gneiss, mica schist, staurolite-mica schist and garnetiferous schist. The *staurolite* occurs in two beds separated by a narrow band of gneiss. The rocks containing it consist largely of quartz and biotite, and are thinly foliated. For the most part the staurolite is in small brown grains and imperfect crystals up to 2 or 3 mm. long, fairly evenly distributed through the rock. Less commonly it has collected into much larger crystals, up to 10 mm., scattered sparsely through the rock.

So far no andalusite, sillimanite or kyanite has been found at this point, which is the furthest south of the staurolite localities.

Goyamin Pool. This is about 4½ miles N.N.E. of the blue kyanite locality, already described, and 3 miles E.N.E. of Marbling Brook. Just to the north-east of the pool is a ridge running east and west which is about 150ft. high. Through it runs a series of schists with a strike about 360 deg. From west to east the succession is: West—(1) large epidiorite dyke; (2) wide stretch of sillimanite schist; (3) narrow band of staurolite schist; (4) kyanite schist; (5) sillimanite schist; (6) kyanite schist; (7) sillimanite schist; (8) dyke and gneiss.

With the exception of portion of the staurolite schist which is highly biotitic, the other rocks are all highly siliceous, carrying 70 to 80 per cent. of fine to coarse quartz grains, the balance being mainly biotite and the characteristic secondary mineral.

The schists which carry the *sillimanite* have the appearance, where weathered, of grey, brown or purplish sandstones of fine to quite coarse texture. They are distinguished, however, by thin lenses of pure white sillimanite following the bedding. These are usually from 0.5 to 2.0 mm. thick and 0.5 to 3.0 cm. long on the cross fracture, and equally wide on the bedding planes. Some material scraped from the lenses was minutely fibrous, colourless and perfectly transparent, with straight extinction and positive elongation. A cross section of the rock shows abundant quartz grains with interleaved biotite, both minerals frequently penetrated by numerous spicules of sillimanite. The visible lenses of the latter appear under the microscope as bundles of almost parallel fibres, sometimes spreading slightly fanwise. Many fibres are bent, others interrupted by gaps in their length. They are from 0.01 to 0.08 mm. in diameter.

One small specimen picked up on this ridge shows satiny and curved masses of white sillimanite with a felt of minute scales of muscovite forming a thin layer on the surface of a quartz vein.

About a quarter of a mile eastwards is a second narrower band of similar sillimanite sandstone or schist, whilst half a mile south-east of Goyamin Pool J. E. Wells has picked up boulders of what is probably the southward extension of the main bed.

A few hundred yards north of the ridge large tough boulders, up to 3 kgm. in weight, of almost pure sillimanite have been picked up on the surface. Their original source is unknown. The only contaminating mineral is quartz which forms about 10 per cent. of the whole mass. The fibrous structure is not everywhere appreciable on the corroded surface, but on a fresh fracture the sillimanite is seen to form a very coarse felt of dense fibrous masses, white, cream-coloured, or pale grey, with a little interstitial

quartz, which itself is penetrated by numerous sillimanite fibres, as shown by the microscope. The specific gravity of the mineral lies between 3.15 and 3.25 and it possesses a straight extinction with positive elongation.

A single somewhat similar specimen picked up a few hundred yards to the north-east consists of practically pure fibrous sillimanite with parallel fibres throughout, reaching a length of 7 cm. It is greyish to yellowish-white in colour, has a specific gravity of 3.26, with Ng slightly over and Np slightly under 1.660. The extinction is straight and elongation positive. Another loose boulder resembles a compressed mass of chips of light brown wood.

There are two beds of *kyanite* schist here, neither of them over two chains (40 metres) wide. Originally the rocks have ranged from a fine sandstone to a coarse grit in texture, and now show in many hand specimens abundant colourless kyanite prisms from almost microscopic size to a maximum of about 3 x 1.5 mm. The relative abundance of visible kyanite varies greatly in different parts of the outcrops. At the surface the rocks are all weathered and ironstained. A section shows about 80 per cent. of quartz grains with strings of heavily ironstained chlorite, probably pseudomorphous after biotite. Many typical kyanite grains are present, usually embedded in the chlorite, whilst small grains of staurolite are not rare, and usually closely associated with the kyanite. Other hand specimens show a fair proportion of a white mica.

In addition to the microscopic *staurolite* above described, a narrow band of schist with visible staurolite occupies a saddle in the ridge, where it lies between kyanite schist and sillimanite schist. Several types of the rock have been recognised. One is highly siliceous and coarsely granular, with staurolite in rather small but abundant grains, and imperfect crystals reaching at most 3 mm. in length. A second is highly biotitic, and in this the secondary mineral is larger, reaching 1 cm. in length, but is very rarely sharply defined by crystal faces. Another of limited extent has a large proportion of creamy white sericite, in which are embedded odd grains and crystals of staurolite up to 5 mm. in length.

To the north, across a small amphitheatre, the staurolite schists outcrop in their least weathered form. The rock is very dark in colour owing to the preponderant biotite and is studded with more or less well formed staurolite crystals up to a centimetre in length. Small lenses and knots of felspathic pegmatite appear in the rock. A section shows the principal constituents of the rock to be biotite, quartz, staurolite and felspar (both microcline and plagioclase). The rock has been analysed by Mr. C. J. LeMesurier with the following results:—

STAUROLITE SCHIST, GOYAMIN POOL.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O
53·01	20·38	3·39	7·44	·09	4·53	2·70	2·07	3·43

H_2O+	H_2O-	TiO_2	CO_2	P_2O_5	FeS_2	Total.	G
1·30	·07	1·18	·45	·11	·08	100·23	2·84

An associated pegmatite "knot" is composed of quartz, microcline, and plagioclase. The largest pegmatite mass in this rock outcrop is about one metre wide and is composed mainly of finely granular albite with subordinate quartz, muscovite and microcline. It is remarkable in containing many crystals of staurolite from a few millimetres up to 2 centimetres in length,

These show the combination *b c m r*, a few being twinned. This is the only case in the writer's knowledge of staurolite being found in a pegmatite, except for one in Canada recorded by W. H. Collins in 1925.

Toodyay Road. Near the N.W. corner of C.G. 145, three-quarters of a mile north of the branch road to Toodyay, sillimanite, kyanite and staurolite have been found in close association.

So far the only specimens of *sillimanite* collected have been three loose boulders, one being practically pure sillimanite, the other two a mixture of this mineral with quartz and a little kyanite.*

The first specimen looks extremely like a number of large chips of silky grained and slightly knotted wood which have been compressed into a solid block. It is unevenly ironstained and is composed of a number of large flat bundles of fine fibres reaching two or three inches (5 to 8 cm.) in length. Some of the cleanest mineral, floated and purified from the attached iron stain, had the following composition:—

SILLIMANITE, MIDDLE CHITTERING VALLEY.

	SiO_2	Al_2O_3	Fe_2O_3	Mn_2O_3	CaO	MgO	H_2O+	H_2O-	Total.	G
Per cent.	41·34	57·22	·90	·15	*nil*	*nil*	·73	·05	100·39	3·15
Mols. ...	688	561	6	1	—	—	45	—		

Analyst: D. G. Murray.

This points to a mixture of about 92.5 per cent. of sillimanite with 7.5 per cent. of quartz (and opal?). With the unaided eye, or mounted in the ordinary way under the microscope, the free silica could not be detected, though apparently it had not all been removed by the preliminary flotation of the mineral with various strengths of CH_2I_2. During the determination of the refractive indices by immersion, the free silica was, however, plainly detectable by its lower refractive index, when immersed in a liquid with the mean index of sillimanite, 1.655. It was found to form thin films on and interstitial fillings between, the individual fibres of the sillimanite bundles, and more rarely to be present as granules traversed in all directions by sillimanite fibres.

The calculated mixture should have a specific gravity of 3.19, if sillimanite be taken at 3.25, and quartz at 2.65. The lower value observed, 3.15, is explained by the hydration of one or both minerals.

The separated sillimanite fibres are colourless and transparent under the microscope, with straight extinction and positive elongation. The refractive indices were determined to be 1.674, 1.656, 1.6545.

The other two specimens consist of vein quartz with some woody-looking masses of sillimanite on one face of each. On the same faces are a few yellowish crystals of kyanite, a millimetre or less in diameter.

This is the furthest north at which sillimanite has been observed.

Kyanite, in addition to the above, is abundant over the slopes of the hill on the southwest side of the road in loose boulders and in a quartz outcrop. It is found in two matrices, viz., in a quartz biotite schist, and in vein quartz. The schist is a reddish rock, banded, but not strongly foliated. The surface is often fairly thickly studded with kyanite prisms up to 8 x 2 mm. These are more abundant in certain thin bands than in the main mass of the

* Since this was written J. E. Wells has discovered sillimanite in several forms to be abundant half a mile due east of this point.

rock. A section of the latter shows rather coarsely granular quartz with biotite and muscovite, approximately in the relative proportions of 80, 12, 8 respectively. A few imperfect crystals of kyanite are noticeable and films of limonite resulting from the partial weathering of the biotite. The kyanite is either colourless, greyish-white, or yellowish-white to the unaided eye.

A large quartz outcrop carries abundant kyanite, particularly in irregular films of mica (biotite and muscovite) which traverse it. In these the prisms reach 2 cm. in length and 4 mm. in width. They are not confined to the micaceous layers, but are much more abundant in them than in the solid quartz. In colour they are either pale yellow, colourless, or white, and in the mica are not infrequently curved, sometimes quite sharply. A concentrate under the microscope showed typical optical properties and revealed an occasional small terminated crystal resembling Danas Fig. 1 on p. 500 of the 7th Edition of his System of Mineralogy.

Very little *staurolite* was observed at this point. Some small crystals and grains were, however, seen in a weathered biotite-quartz schist, and in a boulder of coarsely granular quartz with a little mica. The exact nature of the latter rock is uncertain. A section of the former reveals its constituents (in order of abundance) as: quartz, biotite (partly chloritised), muscovite, staurolite (in ragged grains) and limonite. There are minute inclusions of zircon, etc., in the quartz.

Chittering Lake. The high ridge on the east side of the south end of Chittering Lake has a hard band of granite gneiss on its western end, immediately east of which is a wide series of highly biotitic schists, striking north, and intruded by occasional dykes of epidiorite and hornblende schist.

No sillimanite has been observed at this point.

On the crest of the ridge, about half a mile east of the lake, one band of biotite schist carries *kyanite*, and in places is thickly studded with crystals. These range in size from 5 x 1 mm. to 5 x 1 cm. They are all appreciably blue in colour, the most pronounced being "tyrian blue" (R 47″ i). They are not very transparent, though in some crystals light can be seen through a thickness of 2 mm. One very pale blue crystal 3 mm. thick in two directions is completely transparent. The form in every case is the usual almost rectangular prism with ragged ends. Loose crystals can be found in the soil.

In this place *staurolite* is particularly abundant and better crystallised than anywhere else in the Chittering Valley. In greater or less quantity it is found all across the strike of the schists for about half a mile, some bands being thickly studded with crystals. The matrix is invariably a biotite quartz schist, thinly foliated, and usually containing a high proportion of black biotite. Where the rock is darkest the included staurolite is nearly black in colour; where the rock is paler, the staurolite too is much lighter in colour, about kaiser brown (R. 9′ k). The lighter crystals are usually smaller (3 x 1 or 4 x 2 mm.) and less perfectly developed. In the darker rocks crystals 4 x 2 to 6 x 4 mm. are common. The forms usually developed are *b* (010), *c* (001), *m* (110) and often *r* (101). The basal plane is usually very dull even when the other faces, especially (010) have a brilliant lustre.

In the sides and on the dump of a shallow well, close to the kyanite band on the crest of the ridge, the largest and best developed crystals of staurolite were found. They vary from 5 x 3 up to 20 x 15 mm. in size and

are quite frequently twinned. These twins form oblique or rectangular crosses, the former, which are the more common, being twins on *z* (232), the latter on *r* (032).

A series of measurements of some of the best crystals from this place were made with a Goldschmidt's goniometer by Miss E. A. Bowley, Mr. H. Bowley, and the writer. The significant results, as compared with previous data, are—

	Goldschmidt.	Dana.	Hintze.	E.S.S.	E.A.B. & H.B.
m^1m^4 ...	50°36′	50°40′	50°34′	50°41′	50°37′
				50°41′	50°38′
					50°41′
cr ...	55°14′	55°16′	55°14′	55°17′	55°18′
					55°18′

The mean readings for Chittering Lake staurolite are *mm* 50° 39½′, *cr* 55° 17½′ from which the calculated axial ratios are 0.4732; 1 : 0.6832.

In comparing these figures with those of Dana and Goldschmidt one must remember that the orientation differs with the two authors, Dana's *b* axis being Goldschmidt's *c* axis.

An analysis was made of several of the freshest and cleanest looking crystals having a specific gravity ranging from 3.68 to 3.73. The results were—

STAUROLITE, CHITTERING LAKE.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O
Per cent. ...	30·08	49·94	1·56	12·98	·42	1·54	·38	·14	·06
Mols. ...	501	490	10	181	6	38	7	3	

	H_2O	TiO_2	Total	G
Per cent.	1·92	·90	99·92	3·705
Mols. ...	107	11		

Analyst: D. G. Murray.

The figures show an appreciable excess (5.5 per cent.) of silica over that required by the accepted formula $HFeAl_5Si_2O_{13}$. There is microscopic evidence that most, if not all, of this excess is present as minute inclusions of quartz. A few small scales of biotite were also embedded in the analysed material.

South Bindoon. Of the four minerals only *kyanite* has been observed here. It occurs four miles north of the previous locality on a northerly spur of Red Hill, near the south-east corner of Loc. 1363. Long narrow, white or grey, crystals are plentiful in thin lenses in a siliceous gneiss, and rarely in vein quartz. Details were given in the *Journal of the Royal Society* in 1926, Vol. XII., pp. 63-64. The gneiss has since been described by R. A. Farquharson* as composed of granular quartz with bands of black and white mica.

Wattle Flat. This is about nine miles N. by W. of South Bindoon. Both *staurolite* and *kyanite* occur near the N.W. corner of Loc. 805 in considerable abundance; descriptions have already been given in the *Journal,* Vol. XII., pp. 64, 65, 66. This is the only place in the Chittering Valley so far known in which garnet is abundant in interbedded gneiss and schist. Further north, however, at Gillingarra, garnet is plentiful in an area characterised by abundant staurolite in mica schist. At Wattle Flat kyanite and staurolite occur

* An. Rept., Geol. Surv. W.A., 1926, p. 24.

in separate bands of a similar rock, viz., a quartz-biotite schist. The kyanite in some bands forms ill defined "eyes" composed of a single kyanite individual enveloping a large percentage of quartz. In others it has well defined prismatic boundaries, crystals ranging from 10 to 60 mm. long. In all cases it is white or pale grey in colour.

The *staurolite* is practically never crystallised here, but occurs as lenticular "eyes" enclosing abundant granules of quartz. The schist as a whole carries 73 per cent. SiO_2 and 13 per cent. Al_2O_3, and is therefore much more quartzose than the Goyamin Pool schist whose analysis is given on p. 78.

SUMMARY.

The strip of country, 35 miles long and four miles wide, which embraces the Chittering Valley, is characterised by highly metamorphosed, probably Precambrian, sediments. These consist mainly of quartz and biotite in varying proportions, with less abundant muscovite and sporadic development of chlorite, kyanite, sillimanite, and staurolite, and more rarely of garnet, andalusite and corundum. Andalusite has been completely micacised, and corundum almost so, in the later stages of alteration, the whole area having been subjected to intense metasomatism in which solutions rich in potash took a prominent part. The type of rock most abundant is a highly biotitic, thinly foliated schist, but there are small local developments of quartzite, biotitic sandstone, and muscovite schist. The sedimentary formation is split up into bands by parallel tongues of granite or granitic gneiss, by which also it is flanked on both sides. The whole complex is traversed by dykes of epidiorite and related greenstones. Small quartz veins are not uncommon, and are intimately associated in several places with the development of kyanite and sillimanite. Small pegmatite veins and "knots" are rare but not unknown in the sediments.

The most important localities for the secondary minerals are—

Andalusite (mica pseudomorphs)—Bullsbrook Road.

Kyanite—Bullsbrook Road, Toodyay Road, South Bindoon, Wattle Flat.

Sillimanite—Goyamin Pool, Toodyay Road.

Staurolite—Goyamin Pool, Chittering Lake, Wattle Flat.

Garnet—Wattle Flat.

Corundum—Bullsbrook Road.

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